The Applicability of a Sensor Web Simulator to Evaluate a Future Lidar Mission

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Under a recently-funded ESTO award we are now designing, and will eventually implement, a sensor web architecture that couples future Earth observing systems with atmospheric, chemical, and oceanographic models and data assimilation systems. The end product will be a "sensor web simulator" (SWS), based upon the proposed architecture, that would objectively quantify the scientific return of a fully functional model-driven meteorological sensor web. Our proposed work is based upon two previously-funded ESTO studies that have yielded a sensor web-based 2025 weather observing system architecture, and a preliminary SWS software architecture that had been funded by RASC and other technology awards. Sensor Web observing systems have the potential to significantly improve our ability to monitor, understand, and predict the evolution of rapidly evolving, transient, or variable meteorological features and events. A revolutionary architectural characteristic that could substantially reduce meteorological forecast uncertainty is the use of targeted observations guided by advanced analytical techniques (e.g., prediction of ensemble variance). Simulation is essential: investing in the design and implementation of such a complex observing system would be very costly and almost certainly involve significant risk. A SWS would provide information systems engineers and Earth scientists with the ability to define and model candidate designs, and to quantitatively measure predictive forecast skill improvements. The SWS will serve as a necessary trade studies tool to: evaluate the impact of selecting different types and quantities of remote sensing and *in situ* sensors; characterize alternative platform vantage points and measurement modes; and to explore potential rules of interaction between sensors and weather forecast/data assimilation components to reduce model error growth and forecast uncertainty. We will demonstrate key SWS elements using a proposed future lidar wind measurement mission as a use case.

I. Background

On April 1, 1960, TIROS-1 was launched and became the first US satellite to demonstrate the value of using polar orbiting satellites for global weather monitoring. By 1974, NOAA's SMS/GOES satellite series was complementing the TIROS satellites by providing continuous daytime and nighttime weather monitoring for an entire hemisphere. Today we take for granted the dozens of Earth remote sensing satellites that continuously monitor the land, oceans, and atmosphere and their complementary instruments return terabytes of remotely sensed measurement data daily. Thousands of *in situ* measurement platforms and complex modeling systems, complement these satellites and comprise today's global weather observing, data assimilation, and prediction system. Measurement vantage points extend from the Earth's surface (e.g., Automated Surface Observing System, Doppler radars, ocean buoys), to the troposphere (e.g., radiosondes, dropsondes), higher still to low earth orbit (NOAA's POES, NASA's Earth Observing System), to the unique vantage point of geosynchronous orbit (e.g., NOAA's GOES series).

Notably, today's spacecraft do not differ from their early predecessors in one important respect: with few exceptions, observations are made using independent platforms and science instruments. Information sharing among operational spacecraft, and between spacecraft and *in situ* measurement platforms, does not exist. Predictive model outputs are not used to (re)direct spacecraft instruments to target specific locations where new or additional useful measurements may be made. Targeted observations could be used by data assimilation systems to improve model initial conditions and potentially yield a concomitant reduction in forecast uncertainty. Today's space communications architecture does not readily facilitate collaborative data collection techniques using complementary spacecraft instruments nor take advantage of dynamic and adaptive observing strategies. Instruments

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and platforms lack the ability to respond to rapidly evolving, transient, or variable atmospheric conditions (actual or predicted) by reconfiguring (for example) spatial, temporal, power, or spectral measurement modes: instead, most instruments are simply "ON" all of the time. Those platforms that are able to change data collection modes rely primarily upon manually intensive procedures. Autonomous instrument reconfiguration is the rare "experimental" exception rather than the "routine": many constraints must be considered and changing an instrument's utilization schedule must be planned well in advance of an observation. Disparate mission planning and scheduling systems, designed to meet specific mission measurement needs, are not interconnected. They lack middleware that would foster interoperability and facilitate coordinated opportunistic, multisensor targeted measurements. Instead, measurements are guided by somewhat rigorous data collection schedules.

Today's global weather observing system has matured and evolved during the past four decades: yet it can still be characterized as a large distributed data collection system composed of independent platforms and instruments. Data collection, communications, command, and control (C^4) is organized as a vertically structured system: the infrastructure is not designed to take advantage of near-real-time horizontal multi-sensor data fusion techniques or information exchange across platforms, instruments, and other C^4 systems. In contrast, sensor web observing systems would provide a form of "situational awareness" and provide the ability to dynamically accommodate changes in observation strategies to maximize useful science return. By knowing, for example, that a global survey satellite sensor has detected clouds obscuring a primary target of interest, a pointable sensor on another spacecraft could change its measurement mode and point to a secondary cloud free target. Similarly, if ensemble forecast models were to diverge (e.g., sensitivity to data sparse regions), that information could be used to direct sensor web assets to make targeted measurements that, when assimilated, could improve model initial conditions.

II. Sensor Web Overview

Although some of its intrinsic properties continue to be refined, we have characterized the sensor web as *a coherent set of distributed nodes, interconnected by a communications fabric, that collectively behave as a single, dynamically adaptive, observing system.* The sensor web is composed of sensor, computing, and storage nodes. Sensors may be deployed on or below the Earth's surface, within its atmosphere, and in space. The platforms on which they reside may be stationary or mobile. It is very desirable that sensors have more than one selectable measurement mode. Taking advantage of available local processing and storage, sensor nodes will process their measurement data and invoke algorithms commensurate with the dynamic spatial, temporal, or spectral characteristics of an actual event or a predicted modeled atmospheric state. Nodes interact with one another via the communications fabric: it enables sensor, computing, and storage nodes to exchange and act upon information (e.g., actual or predicted measurements; an instrument's measurement mode; a platform's state of health; and event notification messages). This information is used to influence subsequent sensor measurements, change the initial conditions of a predictive forecast model, or to perhaps invoke a data mining algorithm that correlates new measurement data with retrospective information. Representative node state sequencing and state changes are listed in Tables 1 and 2 respectively.

Node State	*Action*
Event detection	▪ Discriminate and identify significant signals, features, patterns, …
Event notification	▪ Publish (subscribe to) event detection messages for use by other nodes
Event processing	▪ Exchange sensor data and other information ▪ Perform multi-sensor data fusion ▪ Refine event characterization
Node reaction	▪ Exchange node state messages to determine sensor and other available resources ▪ Modify science goals if necessary ▪ Plan new measurements ▪ Schedule new measurements

Table 1. Node State Sequencing

State Change	*Examples*
Spatial	▪ Move sensor to new location ▪ Change measurement resolution ▪ Increase/decrease field of view ▪ Point instrument to new target
Temporal	▪ Change sensor measurement frequency ▪ Invoke a data assimilation or forecast model prior to scheduled run time
Spectral	▪ Select phenomena-specific sensor bands
Power	▪ Change from low to high power mode
Modeling & Data Assimilation	▪ Generate new set of initial conditions ▪ Invoke a nested grid model
Organizational	▪ Modify sensor network topology ▪ Change cluster size ▪ Modify command and control hierarchy
Hardware and software	▪ Reconfigure with event-specific processing algorithm

Table 2. Representative Node State Changes

The communications fabric must support a variety of mediums, protocols, and topologies. Implementation will vary considerably depending upon application-unique functional and performance requirements. Information produced by one node may be transmitted to other nodes using deterministic, triggered, or on-demand reporting methods. Deterministic reporting means that a node will make information available at predictable times. Triggered reporting occurs when a node detects pre-established conditions that warrant information be immediately reported to one or more other nodes. On demand sensor reporting occurs when a node receives a request from one or more other nodes to provide information. Sensor reporting methods will impact the required communications fabric characteristics (e.g., media bandwidth, network topology, communications protocols, network management techniques, and security).

Computing and storage nodes complement the sensor nodes. A data assimilation and predictive weather forecast model is an example of a computing node. Storage nodes (e.g., an intelligent data archive) may mine meteorological repositories and provide derived information, such as historical trends, that could be used to refine where sensor nodes should make targeted observations in advance of the formation of a significant meteorological feature.

The sensor web architecture must permit nodes to aggregate over time, be replaced, upgraded with new hardware or software, and it must accommodate automated rerouting of information from failed or degraded nodes. The architecture must also be scalable to ensure, for example, that an increase in the number of nodes will not introduce significant latencies that impact system throughput and response time. As with large computer networks, a sensor web architecture must accommodate different topologies, heterogeneous command and control mechanisms, and permit two or more sensor webs to logically combine to temporarily form a new, larger sensor web observing system. After the required observations are performed, the system may re-form into smaller, independent subnets. Data and metadata standards must ensure data and information will be exchanged with syntactic and semantic ease.

III. Sensor Web Simulator Rationale

A future global, interactive, sensor web observing system that is able to autonomously perform targeted measurements driven by events detected by other platforms and instruments, or perhaps driven by atmospheric data assimilation systems and predictive numerical forecast models to improve predictive skill, is a very compelling idea. However, investing in the design, implementation, and deployment of such a large, complex observing system would be very costly and almost certainly involve a great amount of risk. When fully implemented, the SWS will serve as an analytical modeling and simulation tool to perform "What-if?" analyses. It will provide engineers and scientists with the ability to objectively define, model, and assess alternative observing system designs, explore candidate dynamic observing strategies and the rules of interaction between its constituent nodes, and quantitatively measure improvements in predictive forecast skill. Such a tool would be able to support cost-performance return on investment trade studies when formulating future missions, instruments, and global observing systems.

IV. Sensor Web Simulator Software Architecture

The SWS is based on the concepts described in "Advanced Weather Prediction Technologies Two way Interactive Sensor Web & Modeling System: Phase II Vision Architecture Study", November 1, 2003[1]. The system described in that weather architecture study consists of five main elements: (i) a Collection System; (ii) a Modeling and Data Assimilation System; (iii) Forecast Operations; (iv) an External Control System; and (v) a Communications, Command and Control System. The SWS will emulate the functions provided by the five elements described in the study.

The SWS will provide an interface to administer the system by configuring new instrument types, platforms, and targeting schemes. An administrator may develop a new instrument or add new nature run data (i.e., a simulated representation of a real global atmospheric state), run simulation tests to validate realistic operation, and evaluate the results. A simulation experiment can include a significant number of platforms and instruments. The majority of these will probably not change from one experiment to the next and it is expected that the simulation operator will want to select sets of these assets to be used for experiments. The SWS will allow the users to define a new base collection of platforms and instruments that can be saved and used in future simulator configurations. Existing base collections from the repository can be modified to fit new experiments. The simulation will allow an operator to set up a base configuration for the simulation trial based on the test scenario. The operator can alter the base configuration according to the scenario test parameters and execute the simulation trial using the new configuration.

Our long term plan for the SWS envisions it to be operated in two modes: a graphical interactive interface mode for those users who want to fine-tune the simulation as it progresses, and a command-line batch processing mode where the user will execute the simulation to completion. In an interactive mode, the operator can control the execution of the simulation and monitor its progress. The simulator will provide the user with graphic displays showing asset locations, flight paths and ground tracks, current weather conditions, etc. An operator will be able to interact with the simulation and can make adjustments to the assets, priorities and analysis products from the sensitivity and weather analysis systems.

An analyst can review simulation output data and compare it with other simulation experiments. Multiple simulation runs (using different sets of values for variables) can be compared to evaluate the outcome of different observing system configurations. The simulator will provide tools for comparison and analysis. It:

- Allows the creation of a set of instruments/platforms for specific simulation experiments.
- Controls the movement and operation of defined instruments/platforms.
- Controls the collection and distribution of observation data by the defined instruments .
- Provides the capability: to perform data assimilation; to generate forecasts from the model; to analyze the forecast results and provide feedback to the system; for the user to interactively control the experiment.

Major architectural components are identified and summarized in the table below.

<table>
<tr><th>Component</th><th colspan="2">Description</th></tr>
<tr><td>Collection System</td><td colspan="2">Gathers information about the environment. For the simulator, this includes the Simulated Observation Generator, Sensor Web Assets and Observation Pre-processing.</td></tr>
<tr><td rowspan="4">Simulated Observation Generator</td><td colspan="2">Provides a simulated representation of the real world (i.e. a “Nature Run”) and the methods necessary to convert that representation into instrument observations consistent with the defined instrument/platform characteristics and the values contained in the nature run.</td></tr>
<tr><td>Nature Run</td><td>A simulated representation of the state of the environment. The nature run data is created using a state of the art weather forecast model at high resolution. The weather forecast model is given an initial state consistent with real world observations. The model is then initiated and generates a free forecast at a set interval (currently 6 hours) from the beginning of the nature run period until the end of the period. The resulting data sets produced by the weather forecast model comprise the nature run. The data sets are validated so that they can be used as the reference, real-world atmosphere. The simulated atmosphere produced by this nature run can then be “sampled” by the SWS platforms to generate simulated observations. The generation of the nature run is not the direct responsibility of the SWS; however, a nature run might be initiated by collaborators to achieve some study goal of interest to the SWS users.</td></tr>
<tr><td>Observation Interpolator</td><td>Accepts nature run data as an input and interpolates it in both time and space to provide corresponding values for simulated observations at the locations and times specified by the instrument observation request. It does not apply any corrections based on instrument characteristics.</td></tr>
<tr><td>Sensor Measurement Interface</td><td>Adjusts the time and space interpolated nature run values provided by the observation interpolator to create a measured value that is consistent with specific instrument characteristics. It provides methods that account for measurement errors, platform or instrument look angles and spatial resolution filtering for specific instrument types to create simulated observations that are consistent with the instruments characteristics.</td></tr>
<tr><td>Sensor Web Assets</td><td colspan="2">A set of objects that are used to instantiate a specific sensor web experiment. Assets may include instruments and platforms, bases and command stations, and communication links.</td></tr>
<tr><td>Observation Pre-Processing</td><td colspan="2">Provides the capability to apply filters, error corrections and other preconditioning functions to selected sets of the simulated observations prior to starting the assimilation process. In particular, it enables the application of statistical errors that require a complete set of observations and cannot be applied during the calculation of individual measurements by an instrument.</td></tr>
</table>

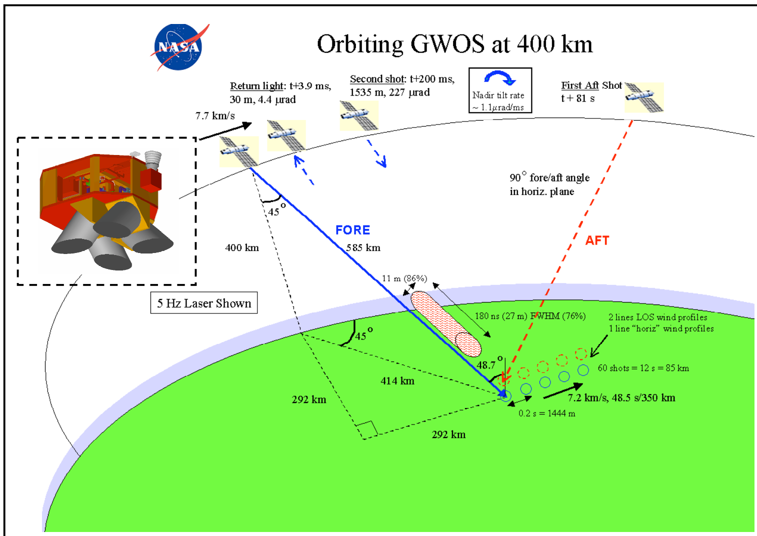
Component		***Description***
Sensor Web Control		Directs the operation of the sensor web assets
	Commanding and Scheduling	Manages sensor web assets by setting their basic collection and movement schedules. Assets are allocated based on collection priorities. Provides schedule information on available assets.
	Targetable Asset Assignment	Analyzes sensitive regions and weather events identified by the forecast analysis system and identifies the most appropriate mobile collection assets required to target them. Uses sensitive regions, event tracking information and other information (e.g. populated areas, shipping lanes) to determine priorities for assigning targetable collection assets. Requests a list of available assets that are within range of sensitive regions or weather events, identifies the most appropriate ones, and sends updated schedule requests to the scheduling system for assets to target the specified areas.
	Asset Coordination System	Guides the usage of sensor web assets. It establishes guidelines that affect how and when the assets can be controlled or the data derived from it can be accessed. This reflects various international and organizational protocols and priorities.
Weather Prediction System		Provides the functionality necessary to merge new observations collected by the SWS into its forecast model and analysis. It will generate ensembles of model forecasts and analyze, identify and track: weather events; determine forecast sensitivity to initial conditions and the geographic areas of sensitivity; and times and types of observations required to improve forecasts.
Model Data Assimilation System		Analyzes the observation data and generates forecasts
	Data Assimilation System	A numerical algorithm that integrates new observational data into a model state supplied by a prior forecast, defining an "assimilation model state" that is used as the initial conditions for a new weather forecast.
	Ensemble Generator	Takes the assimilation model state and produces a set of "ensemble model states" that are used to create ensemble forecasts for doing sensitivity analysis and weather event analysis and tracking.
	Forecast Model	Takes initial conditions from a model state produced by the ensemble generator and produces a free forecast.
Model Data Analysis		Analyzes the forecasts results and generates event tracking and targeting information
	Sensitivity Analysis System	Uses the forecast model output and information relating to weather event locations to produce sensitive regions that can be used to target areas for further observation.
	Weather Event Analysis	Uses the assimilation model state and free forecasts to identify important current or future weather events and provides an estimate of their probability, potential severity, and impact. A list of weather event locations is provided to the sensitivity analysis and weather event tracking components for further processing.
	Weather Event Tracking	Analyzes the assimilation model state and ensemble forecasts to determine the most likely paths of weather events identified by the weather event analysis component.
Simulation Control & Status		Provides the ability to configure, control and monitor the execution of the simulator. It allows the user to interact with the system and determines the flow of control between the each of the system's components
	Simulation Engine	A graphical interface that allows the user to display controls, plots and graphs, and system status.
	User Interface	Drives the simulation process. It provides the control loop that notifies parts of the simulator when to update platform locations, start pre-processing observations, assimilate observations, analyze model sensitivity, apply targeting algorithms, update schedules, and update user displays. It determines when to write restart files, and logs files.

Component	Description	
Operation Statistics	Collects information about the execution of a simulation experiment. It allows the user to look at observation collection and distributions, effectiveness of automatic targeting and asset commanding.	
Simulation Analysis & Reporting	Aids simulation experiment analysis by collecting information, generating statistics and creating reports	
	Statistics Tools	Provide functions that generate various statistics on the simulation output.
	Simulation Report System	Uses Statistics Tools to generate reports (e.g., system metrics, forecast improvements) based on the simulation run. Can be used to quantify the value of a particular simulation.

The SWS requires a significant amount of complex functionality to implement a complete simulation. However, existing software and COTS products will be adapted to meet the simulator's requirements. The Observing System Simulation Experiment (OSSE) work performed at NASA's Goddard Space Flight Center provides a solid foundation for building the simulated observation generator component of the simulator. The Earth System Modeling Framework (ESMF) can provide common interface and data exchange mechanisms that simplify integration of data assimilation and weather forecast models into the SWS system. COTS products, such as Analytical Graphics, Inc. product, Satellite Tool Kit (STK) with its Connect interface and Advanced Visualization Option (AVO), can be used to manage position and movement of collection assets as well as providing a visualization and analysis interface for the system user.

V. Sensor Web Simulator Use Case

In the process of evolving the design of a new system such as the SWS, it is useful to validate it with one or more relevant use cases. We have selected a mission concept study[8], jointly performed by GSFC and LaRC for NASA HQ in cooperation with NOAA, to serve as the use case for our model-driven sensor web ops concept. The objective of the study was to assess the feasibility of a Global Wind Mission and to conduct an instrument and mission concept definition. The objective of the concept mission, the Global Wind Observing Sounder (GWOS), would be to "improve understanding and prediction of atmospheric dynamics and global atmospheric transport" and "improve understanding and prediction of global cycling of energy, water, aerosols, and chemicals."[8] It would achieve these objectives by making "space based direct lidar measurements of vertical profiles of the horizontal wind field to provide a complete global 3-dimensional picture of the dynamical state, clouds permitting and over the oceans for the first time."[8] The anticipated benefits of such an observing system are: "improved parameterization of atmospheric processes in models; advanced climate and atmospheric flow modeling; and better initial conditions for weather forecasting."[8]



Credit: NASA/HQ: Ramesh Kakar, Steve Neek; NASA/GSFC: Jaya Bajpayee, Harry Shaw, Bruce Gentry; LaRC: Michael Kavaya, Upendra Singh

The GWOS mission is envisioned to be a polar orbiting (400 km) sun synchronous spacecraft. The spacecraft is equipped with Doppler lidars that utilize coherent and direct detection measurement methods. Four telescopes comprise the instrument concept. Two telescopes point forward and two point aft oriented 45^0 from nadir as shown (left). As conceptualized for the study, the concept of operation for the instrument is to have each laser make successive measurements via each of the four telescopes. Approximately 81 seconds after the forward shots have been made, aft shots of nominally the same region of interest would be made to achieve accurate wind velocity vector measurements.

Under our ESTO-funded SWS research and development project we plan to demonstrate the potential value of performing GWOS instrument targeted observations. We will modify the GWOS “survey mode” mission ops concept as presently conceived to allow us to investigate the potential benefits of using a predictive forecast model to drive targeted lidar measurements. One such prediction technique we have investigated and plan to use is an estimation of error variance for a meteorological forecast model[9].

The goal of autonomous targeting is to constrain model error growth in ways that have the potential to improve forecast predictive skill. Model error growth typically occurs in “sensitive regions” of the atmosphere. These regions may be: (1) characterized as being either data sparse or completely devoid of data; (2) characterized by sharp gradients in the flow; (3) in baroclinic boundary regions; (4) in areas of high model uncertainty determined from ensemble forecasts; (5) in other areas that are now topics of research. Investigations have shown that the model error in such regions grows non-linearly over time and propagates with the flow. Tasking the observing system (i.e., the lidar in this use case) to collect data within these regions may help to diminish the error. Autonomous targeting would also be useful to track specific atmospheric features of interest, such as hurricanes, or to provide better measurements over areas in which there are large departures between observations and the model’s first guess. The targeting mode use case is designed to supplement and become an extension of the GWOS survey mode use case that would be used in “nominal” daily instrument operations. A candidate story board that we have developed for our scenario is presented below (steps 1-7 are performed first). It is important to realize that this story board is not finalized and it may be modified as we progress with our SWS development work.

Step #	Action
1	Raw data and related telemetry are collected, stored on board, and readied for downlink at the next opportunity. Optimal resolution for the LIDAR defined as: 3 hourly global coverage, 25km horizontal, 250m vertical (1km minimum requirement above PBL). Precision required is 1 m/s
2	LIDAR spacecraft passes over the ground station and downlinks the raw data
3	Raw data is reformatted into Level 0 and transferred via fiber-optic net to ground data processing site.
4	Level 0 data is transferred to ground data processing site and is also transferred to the long-term archive
5	Level 1 product generation (calibration, geolocation, etc.) is performed and product is sent to archive; Level 2 processing scheduled.
6	Level 2 line-of-sight wind product generation is performed and product sent to archive (either u, v, or both wind components may be discerned). Level 2 product distributed via DDS, notifications sent to customers
7	*Operational data assimilation launches:* a non-linear quality control scheme built into the analysis will weight the wind data thus affecting how the data is drawn to the analysis. Wind information is assimilated and a model first guess is produced.
8	*Assimilate Observations:* Data assimilation system (DAS) completes cycle.
9	*Identify targets:* (1) ensemble forecasts are executed to identify model sensitive regions; (2) significant weather phenomena are identified (using vorticity, frontogenesis, jet streak analysis, time tendency, etc.); (3) anomalous patterns identified using corroborating measurements from multiple platforms; (4) large O-F areas identified from DAS metrics; (5) targets of opportunity identified by locating cloud free areas and gaps – cloud mask derived as a composite of all satellite measurements within Δt of lidar observation times
10	*Select Targets:* Multi-layer hierarchical rule-set with operational override; significance assigned based on societal impact, magnitude of uncertainty, coincidence with other platforms
11	*Determine Observing Method*: (1) telescopes pointing along both sides of nadir (symmetric) or telescopes pointing to one side of nadir (asymmetric)1; (2) standard LOS versus unique wind measurements; (3) power and/or frequency modulation. Symmetric or asymmetric observations will be determined based on availability of clear sky (see cloud masking in step 10).
12	Request is passed to External Control to collect observations at specific locations in space and time.
13	On-demand targeting is executed: forecaster may override objectively selected targets in favor of other targets (e.g., hurricane, west coast storm, low-level jet). **See step #9
14	Targeted data requests are passed to External Control, which prioritizes requests and adjusts operations to optimize the quality and throughput of products. **see step #10
15	Next-generation Command & Control system receives lists of targets and manages all observing system assets. **see step #10
16	Level 2 wind vector product generation is performed and product sent to archive. Level 2 product distributed via DDS, notifications sent to customers. **see step #6
17	Return to Step 1

VI. Conclusions

Sensor Web observing systems may have the potential to significantly improve our ability to monitor, understand, and predict the evolution of rapidly evolving, transient, or variable environmental features and events. This improvement, however, will require considerable technology development and almost certainly involve a great amount of risk. A sensor web simulator is described that would allow science, engineering, and mission formulation users to define, model, and objectively assess alternative sensor web system designs and to be able to quantitatively measure any improvement in predictive forecast skill. The potential payoff of introducing sensor web technology into an operational weather forecast system could thus be evaluated before large investments are made. A description of how forecast models could be used to direct lidar instrument measurements of a future Global Wind Mission is also presented.

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